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Land related grievances shape tropical forest-cover in areas affected by armed-conflict

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ABSTRACT

Armed-conflicts often occur in tropical areas considered to be of high ‘conservation-value’, termed as such for their biodiversity or carbon-storage functions. Despite this important overlap, few studies have assessed how forest-biomass is affected by armed-conflicts. Thus, in this paper we develop a multinomial logit model to examine how outcomes of the interactions between carbon-storage, armed-conflict and deforestation rates are linked to social, institutional and economic factors. We use Colombia as a case study because of its protracted armed-conflict, high forest-cover, sustained deforestation rates and on-going peace processes. Our empirical results show that the impacts of armed-conflicts on forest-cover are connected to specific socio-economical processes, such as unequal land distribution and land-grabbing, which typically occurs as part of ‘agricultural colonization’. Findings address a research gap by providing statistically sound evidence for associations between armed-conflicts and land-related grievances, which has rarely been demonstrated empirically. Our results also suggest that forest commons are associated with reduced armed-conflict, and simultaneously provide contributions to carbon storage and to meeting basic needs. Moreover, our forest-conflict transition models provide useful visual means to capture and relay to policymakers- the causes of forest cover-changes in a conflict-affected country. Finally, our findings imply that in dedicating their efforts to resolving land-ownership disputes, the Colombian government might uphold their international climate change commitments via reducing deforestation and hence forest based carbon emissions, while pursuing their national security objective via undermining opportunities for guerrilla groups to operate.

KEYWORDS

REDD+; Forest conservation; Forest conflicts; Armed conflicts; Climate change; Multinomial logit model; Colombia

1. INTRODUCTION

The global demand for increased forest-biomass for climate change mitigation (Harris et al., 2012), in combination with the need for peacebuilding in many countries with large tracts of tropical forests (Hanson et al., 2009), makes the relationship between forest-biomass and armed-conflicts particularly important. That is, tropical forests not only play a key role in global climate change, they also host many of the world's armed-conflicts. Despite this important overlap, the ways in which tropical forest-biomass and armed-conflicts are linked is unclear, as are the ways that specific contextual factors interact and determine forest-cover loss, or conversely help to conserve it (Aide and Grau, 2004; Burgess et al., 2015; Butsic et al., 2015; Hecht and Saatchi, 2007; Ordway, 2015; Sanchez-Cuervo and Aide, 2013).

A better understanding of these relationships could assist policymakers demonstrate the impacts of conflict and post-conflict scenarios on forest-cover, therefore permitting them to justify peacebuilding measures as contributions to carbon-storage efforts and, ultimately, to climate change mitigation (Bates, 2016; Castro-Nunez et al., 2016; Castro-Nunez et al., 2017).

The mechanism for reducing forest-based greenhouse gas emissions (known as REDD+), agreed under the United Nations Framework Convention on Climate Change (UNFCCC) negotiations, is a concrete tool that may be used to jointly address carbon storage and peacebuilding. For instance, when the later successful 2016 peace agreement between the Government of Colombia (GoC) and the Revolutionary Armed Forces of Colombia (FARC) was negotiated, the GoC submitted a Forest Reference Emissions Level (FREL) to the UNFCCC arguing that the cessation of conflict will increase forest-based emissions in the Colombian Amazon by 10 % mostly as a result of deforestation due to increased forest access (MADS, 2014). However, there is, in fact, no agreed theoretical framework for understanding how forest-biomass might be affected by either the continuation or cessation of armed conflicts (Ordway, 2015).

Causal links between forest-cover and armed-conflicts originate in the 'environmental security' field (de Jong et al., 2007). Environmental security literature generally groups such linkages into three possible mechanisms: natural resource scarcity or unequal sharing (Homer-Dixon, 1994); accessibility and competition (Peluso and Watts, 2001); or opportunities that forested areas present for illegal armed groups' covert operations (Collier and Hoeffler, 2004). Moreover, these three foci indicate that forested landscapes are linked to areas with: (1) weak state presence , (2) high-value natural resources for financing combatants and armed groups' hideouts, (3) grievances (for example due to disputes over resources rights and access), (4) a civil population that has been attacked and displaced by armed groups attempting to accumulate assets and expand their territorial control (Collier and Hoeffler, 2004; de Jong et al., 2007; Rustad and Binningsbø, 2012; Rustad et al., 2008). However, despite many arguments linking forests with armed-conflicts, much empirical research indicates that the mere condition of 'tropical forest-cover' is a poor predictor of conflict (Harwell, 2010; Rustad et al., 2008).

Meanwhile, forest-cover changes are principally caused by agricultural expansion, wood extraction and infrastructure, which in turn are driven by various factors including social and political unrest (Geist and Lambin, 2002). Consequently, empirical studies of conflict and post-conflict periods' impacts on forest-cover provide varied and often divergent findings (Baumann and Kuemmerle, 2016; Burgess et al., 2015; Ordway, 2015). Increases in forest-cover have been attributed to: forced migration (Aide and Grau, 2004); a variety of social, institutional and economic behavioural patterns, such as reduced agricultural production due to remittances (Hecht and Saatchi, 2007); and post-war economic development (Rudel et al., 2000). In other analyses, forest-biomass loss has been linked to armed groups' natural resource exploitation (Butsic et al., 2015; Ordway, 2015; Sanchez-Cuervo and Aide, 2013). More recently, it has been argued that the impacts of armed-conflicts depend on specific contextual factors (Baumann and Kuemmerle, 2016), which include armed groups' strategic use of forested areas (Castro-Nunez et al., 2016). Analyses, however, might be faulted for their focus on national and sub-national correlations between tropical forest-cover and armed-conflict variables, without considering other factors contributing to both conflict and forest-cover changes. That is, these studies often fail to account for the complex interplay of social, economic and institutional contexts related to natural resource and forest use (Harwell, 2010). As a result, in contexts of armed conflict, it remains unclear which social, economic and institutional factors are related to positive (increased forest biomass and biodiversity) or negative outcomes (reduced forest biomass and biodiversity).

The objective of this paper is thus to improve the understanding of the links between tropical forests-biomass and armed-conflicts. To this end, we examine how carbon-storage, armed-conflict and forest-cover change are jointly linked to social, institutional and economic factors by using publicly available municipality-level data from Colombia. Specifically, our analysis focuses on how outcomes of the interactions between carbon-storage, armed-conflict and forest-cover change (defined by classifying Colombian mainland municipalities based on three variables carbon storage, armed actions and deforestation rates), are associated with eight factors, namely: demography; conflict victims; illegal activities; land inequality; institutional performance; accessibility; poverty; and forest commons. These factors were selected because each has been associated, albeit in varying ways, with forest-cover changes (Armenteras et al., 2013a; Chadid et al., 2015; Davalos et al., 2011; Dávalos et al., 2014; Etter et al., 2006b; Geist and Lambin, 2002; Sanchez-Cuervo and Aide, 2013), as well as with various levels of conflict in Colombia (Albertus and Kaplan, 2013; Ibáñez and Moya, 2010; Ibáñez and Vélez, 2008; Ross, 2007).

2. THE STUDY SITE

Colombia, located in north-western South America, covers an area of 1.1 million km^2, and is inhabited by approximately 45.4 million people. The country comprises 32 departments (sub-national jurisdictions), which are divided into 1,123 municipalities (including those located in the Archipelago of San Andrés, Santa Catalina and Providencia). Colombia's economy is based on agricultural production (mainly coffee cultivation and cattle ranching), mining and oil production and with an estimated 14% of earth's biodiversity the country has the third highest biodiversity in the world (Armenteras et al., 2006; Orme et al., 2005). Therefore, many people regard protection of Colombia's forests and biodiversity as a global conservation priority (Myers et al., 2000; Olson and Dinerstein, 1998).

Since the 1940s, Colombia has hosted some level of armed-conflict, led by illegal armed groups such as guerrilla insurgencies, paramilitary forces and drug traffickers. Over the last few decades a combination of factors (including unequal land distribution and land grabbing) have displaced more than 3.5 million people from rural areas, thus perpetuating the state of conflict and undermining long-term peace consolidation efforts (Albertus and Kaplan, 2012; Ibáñez and Vélez, 2008; IDMC, 2006; Ross, 2007). Nonetheless, in November 2016, in culmination of over three years of negotiations, GoC and the Revolutionary Armed Forces of Colombia (FARC) signed a peace agreement. This process was facilitated by various countries , including the governments of Norway, Venezuela and Cuba (Zuleta et al., 2013). In parallel to this process, the GoC was developing its National REDD+ Strategy (ENREDD), which is intended to contribute to climate change mitigation via forest conservation and development activities.

Yet, the causes of Colombia's deforestation are not fully understood. The literature indicates differences between regional and local -level drivers of deforestation (Armenteras et al., 2009, 2013b; Sanchez-Cuervo and Aide, 2013), which in turn reflects the country's diverse socio-economic (Armenteras et al., 2011), demographic (Armenteras et al., 2011), political (Sanchez-Cuervo and Aide, 2013), institutional (e.g. regime categories) (Armenteras et al., 2009) and biophysical (Sánchez-Cuervo et al., 2012) -contexts. Some studies claim that the overwhelming driver of land-cover change, across Colombia, is the conversion of forests to livestock pasture (Davalos et al., 2011; Dávalos et al., 2014; Etter et al., 2006a; Etter et al., 2008; Vina and Cavelier, 1999); while others identify illegal crop (i.e. coca leaf) -cultivation as the main reason for deforestation (Álvarez, 2002; Armenteras et al., 2006; Cavelier and Etter, 1995; Dávalos et al., 2011).

While debates continue as to which constitutes the greater cause of deforestation, other studies found that both illegal crop-cultivation and cattle pasture constitute serious drivers of deforestation, in interlinked ways (Chadid et al., 2015; Davalos et al., 2009; Etter et al., 2005; Etter et al., 2006c; Rincon-Ruiz et al., 2013; Van Ausdal, 2009; Vina et al., 2004). For example, in many conflict-affected areas, farmers are clearing forests to produce coca and then investing revenues (from illegal crop sales) in cattle grazing, which is undertaken as a means to strengthen land-ownership claims (Chadid et al., 2015). Yet, despite the prevalence and longevity of this observed pattern, its drivers remain little understood. Early studies found economic returns to be the most significant incentives for cattle-grazing, outweighing other determining factors, such as cultural preferences or the influences of economic or policy instruments (Van Ausdal, 2009). However, more recent studies suggest that cattle-grazing is less influenced by the financial benefits derived from the economic activity, than by other factors, such as the future value of the land and forthcoming land markets (Castro-Nunez et al., 2016; Dávalos et al., 2014).

3. METHODS

A hierarchical cluster analysis (Mahalonobis distance and Ward's method) was computed using R stats package v 3.2.1 to classify the 1,120 Colombian mainland municipalities based on three variables: carbon storage; armed actions; and deforestation rates. This classification defines the possible joint outcomes of the interaction between carbon-storage, armed-conflict and forest-cover change. The analysis considers ‘carbon storage’ as the 50% above ground forest-biomass for the year 2010, divided by total municipal area. Meanwhile, ‘armed-actions’ refers to the average number of attacks, ambushes, harassment and other armed contacts carried out by the Colombian National Army (FF.AA), the FARC and the National Liberation Army (ELN). Meanwhile, ‘deforestation rates’ defines the annual average deforestation rates from 2000 to 2010.

Mainland municipalities’ membership in one of the identified joint outcomes was predicted by using the following independent variables in a multinomial logistic regression analysis: population; conflict victims; area under coca leaf production; land concentration (GINI of Land Index); institutional performance index; distance to (major) markets; unsatisfied basic needs index (NBI); and forest commons area or area under indigenous communities and afro-Colombian territories. The model was developed using STATA version 13. Because of data gaps, the final econometric model considers 1,082 municipalities. Additionally, Kruskal-Wallis post-hoc tests were conducted using R package agricolae v 1.2-4 to identify median differences among joint outcomes categories for each of the eight factors.

The selection of independent variables was undertaken based on a literature review and our understanding of the study site. Economic, social and institutional factors that may influence the outcomes of the relationship ‘carbon storage- armed conflict-deforestation rate’ were selected to reflect major arguments on the links between forest-cover and armed-conflicts

(Collier and Hoeffler, 2004; de Jong et al., 2007; Homer-Dixon, 1994; Le Billon, 2001; Peluso and Watts, 2001; Rustad et al., 2008), as well as the drivers of forest-cover changes (Geist and Lambin, 2002). Each of the selected variables has been linked with land-use change patterns in Colombia (Armenteras et al., 2013a; Chadid et al., 2015; Davalos et al., 2011; Dávalos et al., 2014; Etter et al., 2006b; Sanchez-Cuervo and Aide, 2013), as well as with armed-conflict outcomes (Albertus and Kaplan, 2012; Ibáñez and Vélez, 2008; IDMC, 2006; Ross, 2007). The explanation of the selected independent variables, their sources and the period analyzed are synthesized in Table 1.

Table 1 Description of explanatory variables selected to predict municipalities' membership in defined outcomes.

Variable	**Description and measurement**	**year**	**Source**
Population	Average total number of inhabitants	2001-20010	DANE
Coca area	Average area cultivated with coca in hectares	2001-2010	SIMCI
Forests commons	Hectares under Afro Colombians and Indigenous communities ownership	2001-2010	IGAC
Unsatisfied Basic Needs Index	The index (from 0 to 100; No basic need satisfied=0, all basic needs satisfied=100) is determined through five indicators: adequacy of housing; degree of household overcrowding; adequacy of basic household services; degree of economic independence of the household; household with school-age children who are not attending school.	2005	DANE
Distance to markets	Average linear distance in kilometers to major markets.	2001-2010	IGAC
Land GINI	Average of land Gini index. The index measures land distribution. Values equal to 0 represents perfect equality, while an index of 1.0 implies perfect inequality.	2001-2010	IGAC
Fiscal Performance	Average of Fiscal Performance index. The index summarizes in a single measurement:1) Percentage of revenues for operating; 2) Magnitude of the debt; 3) Percentage of income due to transfers; 4) Percentage of revenue accruing from own resources; 5) Percentage of total investment spending and 6) Capacity savings.	2001-2010	DNP
Victims (Index)	Principal Component Variable of the average total number of forced displacements by 'place of displacements' and average 'number of civilians and militaries impacted by landmines, improvised explosives and unexploded munitions'.	2001-2010	HRO
Forced displacements †	Average number of forced displacements by 'place of displacements'.	2001-2010	HRO
Affected by landmines †	Number of civilians and militaries impacted by landmines, unexpected explosives and unexploded munitions	2001-2010	HRO

† Variable used to construct the Victims Index

Analyses were based on official data-sets available for public use. Above Ground Biomass (AGB) maps used were those developed by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) using plot-based forest inventories, Landsat satellite images and allometric equations (Alvarez et al., 2012; Phillips et al., 2016; Phillips et al., 2011). Forest cover maps for the year 2000 and 2010 were also developed by IDEAM (Cabrera et al., 2011). Data on armed-conflicts and conflict victims is compiled by the Observatory for Human Rights and International Humanitarian Law of the Vice Presidency of Colombia (HRO) and is available at municipality level for the years 1998 – 2014. Data on illegal crops production was compiled by SIMCI (the Integrated System for Monitoring Illegal Crops). Meanwhile, the social, institutional and economic indicators used, were those developed by the Colombian National Administrative Department of Statistics (DANE), the Department of National Planning (DNP) and the Geographic Institute Agustin Codazzi (IGAC).

The study's data-sets vary in terms of their spatial units of reference. While aggregate data on armed-conflict, social, institutional and economic factors use municipal boundaries as a reference, forest-cover data are raster-based; that is, these are estimated with a spatial resolution equal to that of the source map (i.e. 30 x 30 meters per pixel). Therefore, to obtain an appropriate spatial unit of analysis, we used standard spatial intersections of the municipal polygons with the data on forest-cover. For the assignment of attributes based on municipal geometries, we followed an area-based approach (i.e. the value estimated for each variable was attributed to municipal geometries, as previously defined). Variables other than carbon were defined over the ten-year period from 2001 to 2010, due to data availability. An exception is the variable NBI, which was defined for the year 2005. Meanwhile, the variable victims was defined by an index extracted through principal component analysis of average number of internally displaced persons (IDPs) and average number of civilians and combatants impacted by landmines, unexpected explosives and unexploded munitions. The two constituent variables load on a single component with an explained variance over 75% (see Table 2 for more details). Our victim index is consistent with the oft-cited finding that victims of the Colombian conflict largely comprise civilians displaced by armed groups, in their efforts to accumulate land (Cubides, 1999; Ibáñez and Vélez, 2008). Nonetheless, it is important to note that this land-grabbing strategy is predominantly undertaken by armed groups (including paramilitary) that were not considered in this analysis. The choice of focus on the FARC and ELN was based on the research coinciding with the GoC-FARC and the GoC-ELN peace processes, and additionally due to data accessibility constraints. All graphics were prepared using the ggplot2 library in R. stats package v 3.2.1. In order to visualize and describe non-parametric relationships between carbon storage and armed conflicts, and between deforestation rates and carbon storage, we used the spline function in R (Eilers and Marx, 1996).

Table 2 Victims index (Principal component analysis)

					Principal component loadings. component normalization : sum of squares (column)=1	
Component	Eigenvalue	Difference	Proportion	Cumulative	Variable	Component1
Component1	1.50571	1.01142	0.7529	0.7529	Forced displacements	0.7071
Component2	0.494292	-	0.2471	1	Affected by landmines	0.7071

Method: principal component analysis; number of parameters=2; retained component=1; rotation: oblique promax (Kaiser off).

4. RESULTS

4.1 Joint outcomes categories

The hierarchical cluster analysis resulted in a four-part classification of Colombian mainland municipalities (n=1120). The geographic distribution of municipalities according to joint outcomes categories (Figure 1) is consistent with patterns of spatial distribution of forest-carbon storage, conflict variables and deforestation rates reported in other studies (Castro-Nunez et al., 2017). There are 98 municipalities in the sample of 1,120 classified as joint outcome 1; 80 as joint outcome 2; 681 as joint outcome 3; and 261 as joint outcome 4. Based on the combination of values that define the joint outcomes categories (Table 3 and Figure A.1), we refer to these classifications as:

- *Stable forested municipalities*: municipalities clustered as joint outcome 1 or those that are little affected by conflicts, very little affected by deforestation and have very high carbon storage;
- *Unstable partially-forested municipalities:* municipalities clustered as joint outcome 2 or those that are highly affected by conflict, affected by deforestation and have high carbon storage;
- *Stable partially-forested municipalities:* municipalities clustered as joint outcome 3 or those that are little affected by conflict, affected by deforestation and have low carbon storage; and
- *Stable non-forested municipalities:* municipalities clustered as joint outcome 4 or those that are little affected by conflict, very highly affected by deforestation and have very low carbon storage.

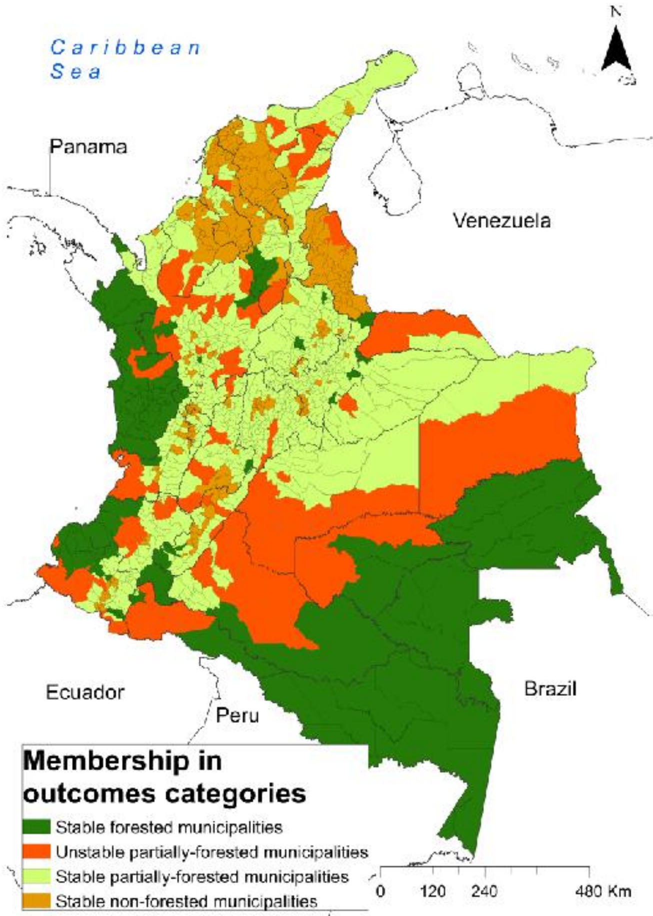

Figure 1 Geographic distribution of municipalities according to joint outcomes of the interactions between carbon storage, armed actions and deforestation rates.

Table 3 Combination of values of carbon storage, armed actions and deforestation rates for the four joint outcomes.

Variable	Mean	SD	Median	Min	Max
***Joint outcome 1* (98 municipalities)**					
Carbon Storage (t/ha)	80.58	17.49	75.99	56.74	126.66
Armed actions (actions/yr)	2.17	1.78	1.60	0.10	6.60
Deforestation rate (%/yr)	0.53	0.32	0.44	0.06	1.49
***Joint outcome 2* (80 municipalities)**					
Carbon Storage (t/ha)	48.80	30.58	53.34	2.19	122.80
Armed actions (actions/yr)	17.75	10.64	14.60	6.50	55.50
Deforestation rate (%/yr)	1.55	1.07	1.22	0.23	5.35

***Joint outcome 3* (681 *municipalities*)**					
Carbon Storage (t/ha)	15.79	14.77	10.87	0.00	59.00
Armed actions (actions/yr)	1.42	1.92	0.60	0.00	9.30
Deforestation rate (%/yr)	1.95	1.08	1.75	0.00	5.26
***Joint outcome 4* (261 *municipalities*)**					
Carbon Storage (t/ha)	7.89	14.83	1.38	0.00	77.74
Armed actions (events/yr)	0.84	1.80	0.30	0.00	14.70
Deforestation rate (%/yr)	6.49	1.67	6.03	4.20	10.00

Figures 2A and 2C show differences in the distribution of the data among joint outcomes categories with respect to carbon-storage, armed-conflict and forest-cover change. There is no linear association between carbon storage and armed actions (Figure 2A). Likewise, there is no linear association between average deforestation rates and carbon storage (Figure 2C). However, the fitted trend of the data shows non-parametric relationships between carbon storage and armed conflicts (Figure 2B), as well as between deforestation rates and carbon storage (Figure 2D).

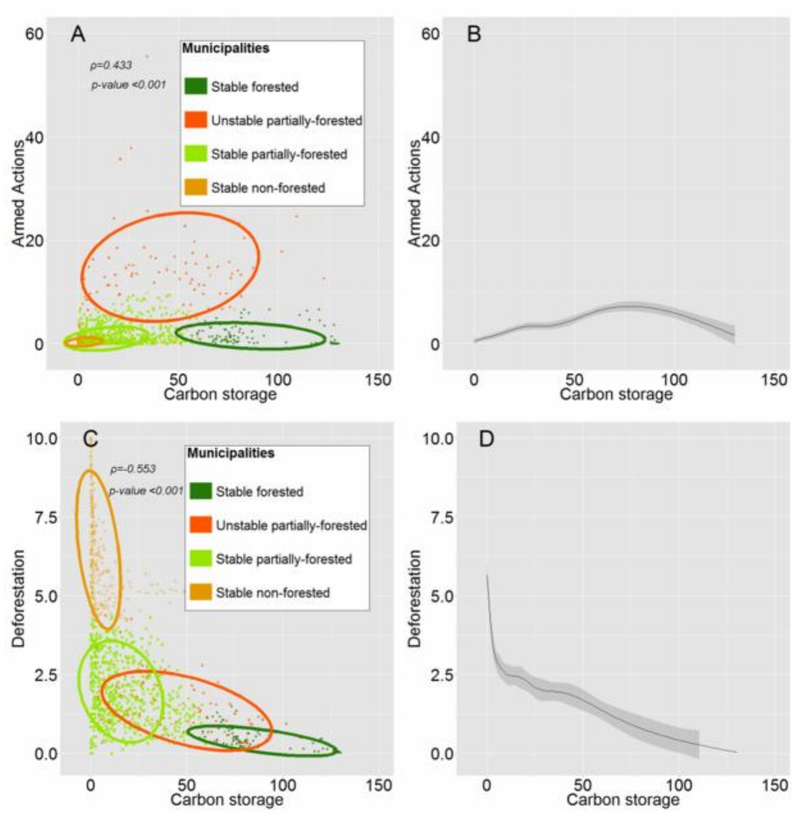

Figure 2 Multiple joint outcomes and non-parametric relationships between carbon storage and armed conflicts (A and B) and between deforestation rates and carbon storage (C and D) in Colombian municipalities.

4.2 Multinomial logistic regression model

The descriptive statics of independent variables selected to predict municipalities' membership in defined joint outcomes are presented in Table A.1. Results of the multinomial logistic regression model are presented in Table 4. The final model proved resilient to a series of post-estimation tests. Likelihood ratio tests for independent variables (Ho: B = 0) and Wald tests for simple and composite linear hypotheses about individual parameters were not significant for any variable. The Small-Hsiao test for violation of the IIA assumption was not significant. Standard errors calculated using the Huber-White sandwich estimator did not produce significantly different results. Regression diagnostics do not indicate that any observations unduly influenced the results.

Table 4 Multinomial logit regression results

Independent variables	*marginal effects*	*std. error*	*z-value*	*Prob >z*
Stable forested (n = 68)				
Population (#)	-1.25E-06	0.00E+00	-4.440	0.000***
Victims (index)	2.88E-03	6.45E-03	0.450	0.655
Coca (has)	9.13E-05	4.00E-05	2.450	0.014**
Land concentration index (GINI)	-7.31E-02	3.76E-02	-1.950	0.052*
Fiscal performance index	-3.14E-03	1.14E-03	-2.750	0.006***
Distance to markets (Km)	7.05E-05	5.00E-05	1.400	0.161
Unsatisfied basic needs index	7.08E-04	2.70E-04	2.650	0.008***
Forests commons (has)	2.96E-07	0.00E+00	2.870	0.004***
Unstable partially-forested (n = 77)				
Population (#)	1.10E-07	0.00E+00	1.470	0.140
Victims (index)	4.63E-02	8.77E-03	5.280	0.000***

Coca (has)	1.34E-04	4.00E-05	3.170	0.002***
Land concentration index (GINI)	8.97E-02	6.13E-02	1.460	0.143
Fiscal performance index	-8.97E-04	1.29E-03	-0.690	0.488
Distance to markets (Km)	1.89E-05	9.00E-05	0.210	0.836
Unsatisfied basic needs index	-2.21E-04	3.60E-04	-0.620	0.536
Forests commons (has)	3.29E-07	0.00E+00	2.750	0.006**
Stable partially-forested (n = 677)				
Population (#)	6.70E-07	0.00E+00	1.990	0.046**
Victims (index)	1.63E-03	2.59E-02	0.060	0.950
Coca (has)	3.58E-05	1.70E-04	0.220	0.830
Land concentration index (GINI)	2.23E-01	1.22E-01	1.820	0.069*
Fiscal performance index	7.28E-03	2.36E-03	3.080	0.002***
Distance to markets (Km)	3.13E-04	1.90E-04	1.620	0.105
Unsatisfied basic needs index	-2.95E-03	9.50E-04	-3.110	0.002***
Forests commons (has)	3.26E-06	0.00E+00	5.550	0.000***
Stable non-forested (n = 260)				
Population (#)	4.71E-07	0.00E+00	2.550	0.011**
Victims (index)	-5.09E-02	2.33E-02	-2.180	0.029**
Coca (has)	-2.61E-04	1.60E-04	-1.680	0.092*
Land concentration index (GINI)	-2.39E-01	9.79E-02	-2.450	0.014**
Fiscal performance index	-3.24E-03	1.76E-03	-1.840	0.066*
Distance to markets (Km)	-4.03E-04	1.70E-04	-2.410	0.016**
Unsatisfied basic needs index	2.46E-03	8.80E-04	2.810	0.005***
Forests commons (has)	-3.88E-06	0.00E+00	-6.440	0.000***

Number of observations = 1082

Likelihood ratio _ 2(24) = 556.02

pseudo R^2 = 0.257

Prob. __ 2 = 0.0000

* p<0.1, p<0.05, p<0.01

'Dependent Variable' = joint outcomes of the interaction between carbon storage, armed conflict and deforestation rate; 'Population'= total number of inhabitant in municipalities' urban and rural areas; 'Victims'= principal component analysis of: average number of internally displaced persons and average number of civilians and militaries impacted by landmines, improvised explosives and unexploded munitions; 'Coca'=average area in hectares under production of coca leave; 'Land concentration index' =average Gini of land Index; 'Fiscal performance index'= average fiscal performance Index; 'Distance to markets' = distance to major markets (Kilometres); 'Unsatisfied basic need index = index of unsatisfied basic need for the year 2005; 'Forest commons' = area under control of indigenous communities and Afro-Colombians (hectares). Explanatory variables were defined over the ten year period from 2001 to 2010, with the exception of 'unsatisfied basic needs', which was defined for the year 2005.

We find that *stable forested* municipalities are positively associated with the production of coca and land area under forests commons and poverty, and that these are negatively associated with land concentration, municipal fiscal performance and population. Municipalities categorized as *unstable partially-forested* are positively associated with coca production, conflict victims and forest commons. *Stable partially-forested* municipalities are positively associated with land concentration, fiscal performance, forest commons and population; while these are negatively associated with poverty. We found an unexpected positive association of poverty with municipalities categorized as *stable non-forested.* These municipalities are also positively associated with population, whereas they are negatively associated with distance to major markets, fiscal performance, coca production, victims, land concentration and area under forest commons.

Non-linear responses to socio-economic indicators were evident in our analysis. Larger populations are associated with a lower probability that municipalities will be classified as *stable forested* (Figure 3A). Municipalities with larger coca areas are more likely to be classified as *unstable partially-forested* and less likely to be classified as *stable non-forested* (Figure 3B). Municipalities with a higher number of victims are more likely to be classified as *unstable partially-forested* and less likely to be classified as stable non-forested (Figure 3C). Additionally, municipalities with larger concentrations of land are more likely to be classified as *stable partially-forested* municipalities and less likely to be classified as *stable non-forested* (Figure 3D). Higher fiscal performances are associated with a higher probability that these municipalities will be classified as *stable partially-forested* and lower probabilities that these municipalities will be *stable non-forested* and *stable forested*.

Meanwhile, greater distance to markets has a negative effect on the predicted probability of being classified as *stable non-forested municipality*, and no effect on the probability of being classified in the other three categories. Municipalities with larger areas under forest commons are more likely to be classified as *stable partially-forested* and less likely to be classified as *stable non-forested* (Figure 3E). The unsatisfied basic needs index (NBI) has a positive effect on the predicted probability of being classified in both the *stable forested* and the *stable non-forested categories*, as well as a negative effect on the predicted probability of being classified as *stable partially-forested*. However, municipalities with higher populations with NBI are more likely to be classified as *stable non-forested municipalities* and less likely to be classified as *stable partially-forested* (Figure 3F).

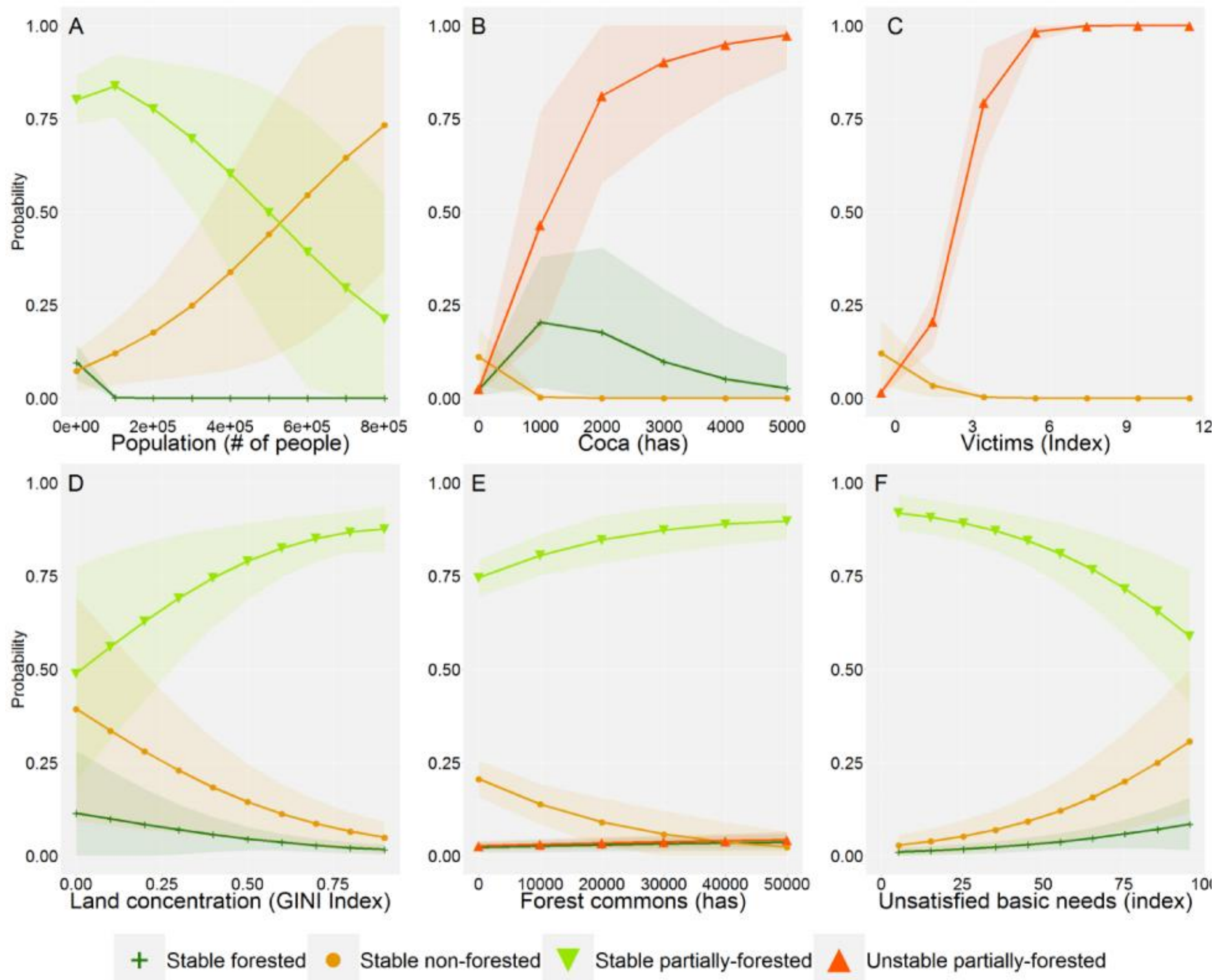

Figure 3 The effect of social, institutional and economic factors on the probability of being classified in defined municipality categories. (A) The effect of population on the predicted probability of being classified in: stable forested; stable partially-forested; or stable non-forested municipalities. (B) The effect of area under coca production on the predicted probability of being classified in: stable forested; or unstable partially-forested municipalities. (C) The effect of victims on the predicted probability of being classified in: unstable partially-forested; or stable non-forested municipalities. (D) The effect of land concentration on the predicted probability of being classified in: stable forested; stable partially-forested; or stable non-forested municipalities. (E) The effect of forest commons (area under indigenous communities and Afro-Colombian collective lands) on the predicted probability of being classified in: stable forested; unstable partially-forested; stable partially-forested; or stable non-forested municipalities. (F) The effect of unsatisfied basic needs on the predicted probability of being classified in: stable forested; unstable partially-forested; stable partially-forested; or stable non-forested municipalities.

Results also indicate that the variability of factors for specific joint outcomes categories with a small number of municipalities (Table A1) jeopardizes non-linear relationships (particularly with respect to population and coca) in the sense that, despite the prediction line being non-linear, the point-wise confidence interval shows that there is no statistical non-linearity. Specifically, the high variability of population for *stable non-forested* and for *stable partially forested* municipalities is reflected in the point-wise confidence intervals, indicating no statistical non-linear relationships (Figure 3A). Similarly, the high variability of coca area within municipalities classified as *stable forested* is reflected in the point-wise confident interval, indicating that the probabilities of *stable forested* are non-linear with respect to hectares of coca (Figure 3B). Although this constitutes a caveat of our approach, it does not have implications for the forest-conflict transition models proposed below.

4.3 Median differences in selected explanatory variables among defined joint outcomes

The Kruskal-Wallis Test statistics are highly significant for: Population (χ 2 (3) = 98.82), Coca area (χ 2 (3) = 101.196), Forest commons (χ 2 (3) = 234.14), NBI (χ 2 (3) = 121.65), Distance to markets (χ 2 (3) = 101.196), GINI Index (χ 2 (3) = 34.20), Fiscal performance (χ 2 (3) = 61.81), and Victims (χ 2 (3) = 216.52). Therefore, it was meaningful to apply post-hoc tests to identify median differences in the eight factors among the defined joint outcomes categories. Tests confirm differences ($p<0.1$) in the distribution of values of explanatory variables among the joint outcomes categories. More specifically, stable forested municipalities are distinct from unstable partially-forested municipalities due to differences in: population ($p<0.01$); victims ($P<0.01$); land concentration ($p<0.1$); unsatisfied basic need ($p<0.01$); distance to markets ($p<0.01$); and fiscal performance ($p<0.01$). Among factors differentiating unstable partially-forested municipalities from stable partially-forested are: increased population and forest commons ($p<0.01$); and reduced population ($p<0.01$); and poverty ($p<0.01$). Whereas, factors differentiating stable partially-forested from stable non-forested municipalities are: increased poverty ($p<0.01$); and reduced land concentration ($p<0.01$); and forest commons ($p<0.1$). Identified differences are consistent with the multinomial regression model's findings.

5. DISCUSSION AND CONCLUSION

Interactions between forest-cover and armed conflicts generate multiple outcomes (Baumann and Kuemmerle, 2016; Burgess et al., 2015; Butsic et al., 2015; Ordway, 2015; Sanchez-Cuervo and Aide, 2013). A deeper understanding of this relationship, therefore, requires simultaneous consideration of these outcomes and the social, economic and institutional factors that drive them (Baumann and Kuemmerle, 2016). Our analysis has operationalized these insights with a statistical approach that incorporates the complexity of multiple outcomes, as well as of the factors that may be at play in their occurrence. This led to identification of four different types of associations between forest-cover and armed-conflicts that are differentiated by social, institutional and economic factors.

Associations indicated by the multinomial logistic regression model, in combination with variations among the joint outcomes categories confirmed by post-hoc tests, suggest that: armed-conflicts and forest-cover change patterns in conflicted-affected areas of Colombia are connected to specific socio-economic factors present during the agricultural colonization processes. Such factors include illicit crop production, unequal land distribution, low institutional capacities and forced displacements. These findings address a research gap by providing statistically sound evidence for associations between armed-conflict and land-related issues (including unequal land distribution and land-grabbing) in a tropical forested country, which has often been assumed (Ibáñez and Vélez, 2008; Ross, 2007; Van Leeuwen and Van Der Haar, 2016), but rarely demonstrated empirically.

While remaining cautionary about the causality of the associations we report, findings allow us to propose forest-conflict transition models for Colombia (Figure 4). The models were inspired by non-parametric relationships between: carbon-storage and armed-conflicts (Figure 1B); and deforestation-rates and carbon-storage (Figure 1D). Using these models we depict the dynamic links between forest-cover and armed-conflict and additionally propose a theoretical framework for examining how Colombia's land-cover changes are associated with colonist farmers, illegal actors (e.g. traffickers and armed groups), unequal land distribution and land-grabbing. Models suggest that, during agricultural colonization processes, conflicts increase in line with forest carbon losses, but that (at a certain stage of carbon-loss) conflict then decreases. This tendency is described by an inverted U-shape relationship between conflict and forest carbon-storage. Meanwhile, carbon contents decrease and deforestation rates increase steadily over time; apparently this is particularly relevant in municipalities with few areas assigned to forest commons. Whereas, deforestation rates increase until forest and poverty indicators reach their lowest levels.

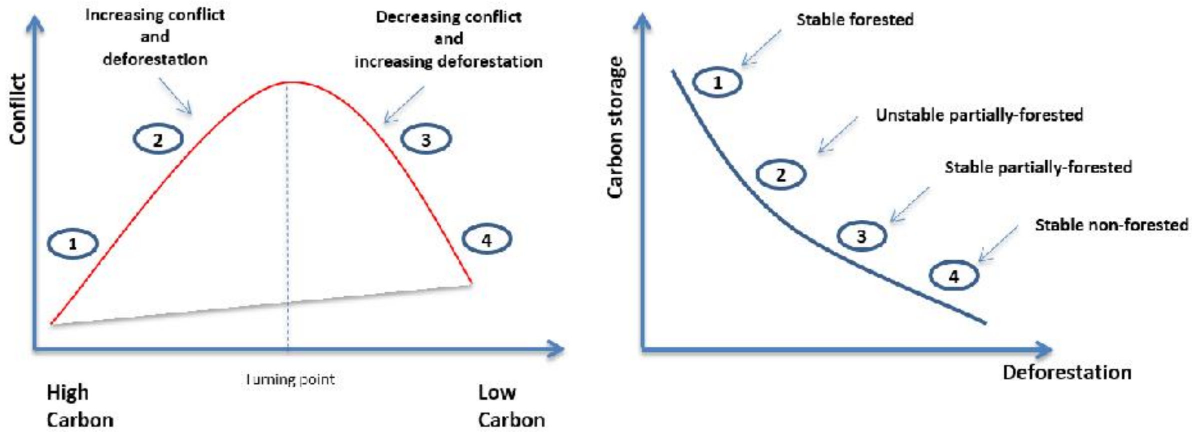

Figure 4 Forest-conflict transition models for Colombia

The models hypothesized that unpopulated forests in Colombia (refer to points marked as ‘1’ in Figure 4) provide opportunities for operating guerrilla groups, by providing hideouts and resources to finance war (i.e. outputs of coca plantations). They also hypothesize that increases in levels of conflict and rates of deforestation (probably in tandem with forced displacements and land grabbing) coincide with the expansion of agricultural frontiers (see points marked as ‘2’ in Figure 4). The models also illustrate that, at a certain point when colonization and land grabbing are completed, levels of conflict decrease and institutional indicators improve (see points marked as ‘3’ in Figure 4). Moreover, they show that the redistribution of access to land begins as wealth indicators decline (see points marked as ‘4’ in Figure 4).

The hypotheses in the models are consistent with arguments that agricultural colonization fronts in conflict-affected areas of Colombia are usually related to cattle pasture and the illicit crop economy (Chadid et al., 2015; Etter et al., 2006c), as well as to arguments that cattle pasture production and illicit crops are tools to access and enhance the value of previously marginal and conflict-affected land (Castro-Nunez et al., 2016; Dávalos et al., 2014). They are also consistent with arguments that the conflict in Colombia is related to land-use competition and land-access inequalities (Albertus and Kaplan, 2013; Ross, 2007), even though forested areas are linked with the historical causes of conflict and play an important role in the strategies of armed groups (Castro-Nunez et al., 2017; Collier and Hoeffler, 2004; de Jong et al., 2007; Homer-Dixon, 1994; Peluso and Watts, 2001; Rustad et al., 2008).

The hypotheses are supported by combined results from the multinomial logistic regression model and Kruskal Wallis tests. Although the models require further testing, they nonetheless already provide useful visual depictions of the environmental security field's major arguments (i.e. opportunities, scarcity, and accessibility) on the relationship between forest-cover and armed-conflicts. Visual models also provide useful means to capture- and relay to policymakers- the causes of forest cover-changes in a conflict-affected country. Specifically, models suggest that, for Colombia, the following concurrent conditions are conducive to both continued armed-conflict and large-scale forest-cover changes: (1) proximity to forested areas that might serve as cover for armed groups and illegal activities; (2) availability of high-value natural resources (such as outputs of illegal crop production to finance guerrilla movements and agricultural colonization); (3) sites of grievances (such as agricultural colonization frontiers with people displaced by land-access inequalities and violence); and (4) competition for the power derived from the control (and grabbing) of scarce resources, such as land.

Based on our findings we argue that: (1) the impact of armed conflicts on forest biomass depends on how specific socio-economic processes (e.g. colonization processes) intersect with armed groups' uses of forested areas (e.g. sources of valuable resources and sources of land assets); (2) reducing tropical deforestation is not only a function of land management (Putz and Romero, 2012), economic incentives (Tacconi, 2012) and forest governance (Phelps et al., 2010) - it is also about illegal activities and, importantly, about addressing the historical reasons for violence, which in Colombia are related to inequality and grievances relating to land-ownership and forced displacements; and (3) if governments wish to retain their natural forests for various conservation purposes (such as avoiding forest-carbon stock losses, while reducing opportunities for guerrilla groups to operate), they ought to target development activities for farmers living at agricultural frontiers and forest dependent people, rather than leaving these groups to suffer the negative impacts of conflicts, thus fueling the cycle of grievances and disputes over land rights. In that respect, our results indicate that the presence of forest commons (or collective lands) apparently reverses and reduces the causes of conflicts, while simultaneously providing contributions to carbon storage and to meeting basic needs, as is argued by many others (Chhatre and Agrawal, 2008; Chhatre and Agrawal, 2009).

Finally, the findings have important practical implications for conflict-affected tropical countries that are pursuing REDD+ (Bates, 2016; Castro-Nunez et al., 2016; Castro-Nunez et al., 2017). In the Colombian context, the GoC has declared its commitment to meeting forest-based emissions reductions (the Paris Agreement) and biodiversity conservation (the Aichi) targets. It is anticipated that strategies leading to the achievement of forest conservation goals (whether for climate change mitigation or for biodiversity) will be implemented along with the GoC-FARC peace agreement commitments (Republica-de-Colombia and Fuerzas-Armadas-Revolucionarias-de-Colombia, 2014). This implies facilitating forest conservation in a post-conflict scenario, while simultaneously addressing the historical reasons for violence, as well as the emerging challenges related to the accomplishment of the peace agreements (Baptiste et al., 2017; Negret et al., 2017). To do so will require innovative approaches, underpinned by robust analyses of the contexts. The analytical framework applied in this research could assist in better understanding the complex dynamics at play and thus inform decisions about how to appropriately target the multiple aims of securing peacebuilding, biodiversity conservation and forest carbon-storage. This stands in contrast to overly simplistic explanatory models of the relationships between conflict and forest-cover, based on unsubstantiated assumptions. However, challenges to doing so include that armed-conflicts in many countries have impeded the collection of reliable and recent socio-economic data. Nonetheless, even with limited variables, the proposed methodology would provide better insights than those generated by current approaches. Moreover, when historical data is available, the proposed methodology could be enhanced and conflict transition models for tropical forested countries better estimated.

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Appendices

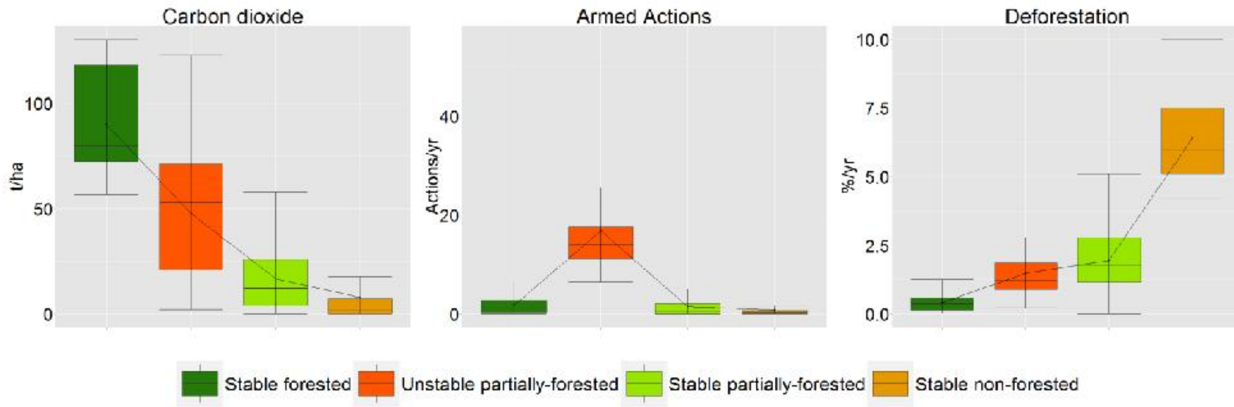

Fig A1 Municipalities' descriptive statistics according to their membership in combined outcomes of the interactions between carbon storage (t/ha), armed actions (number of actions) and deforestation rate (hectares/year)

Table A.1 Descriptive statistics of variables selected to predict municipalities' membership in defined joint outcomes

Variable	Mean	SD	Median	Min	Max
***Full set of Colombian mainland municipalities* (1120)**					
Population	38507.31	234738	12590.9	236.4	6890847.5
Coca area	79.18	391.44	0	0	5136.5
Forests commons	23399.21	264355.7	0	0	6909088
Unsatisfied Basic Needs (Index)	44.97	20.9504	42.57	5.36	100
Distance to markets	128.57	108.47	102.01	0	926.47
Land GINI	0.69	0.11	0.70	0	0.98
Fiscal Performance	59.19	5.84	58.38	39.91	83.35
Victims (index)	2.83E-10	1.23	-0.44	-0.55	12.78
Forced displacements†	317.77	664.42	74.7	0	8390.2
Affected by landmines†	0.71	2.379	0	0	34
***Stable forested municipalities* (98)**					
Population	11494.96	10595.95	8827.95	236.4	68452.5
Coca area	254.67	648.11	14.2	0	3238.8
Forests commons	219462.57	903800.5	8675.27	0	6909088
Unsatisfied Basic Needs Index	68.92	24.46	69.7	13.01	100
Distance to markets	280.37	218.83	184.20	14.50	926.47
Land GINI	0.60	0.20	0.62	0	0.98
Fiscal Performance	55.47	4.96	55.71	40.41	67.75
Victims (index)	-0.060	0.60	-0.27	-0.55	2.86
Forced displacements†	337.69	483.72	188.05	4	3124.2
Affected by landmines†	0.44	0.82	0	0	4
***Unstable partially-forested municipalities* (80)**					
Population	194126.09	832321.8	30773	6340.5	6890847.5
Coca area	47.92	29.04	52.98	2.19	122.80
Forests commons	54784.07	176801.3	4965.32	0	1092513
Unsatisfied Basic Needs Index	51.54	24.12	48.21	9.16	100
Distance to markets	153.56	96.29	136.02	0	519.15
Land GINI	0.67	0.13	0.67	0.30	0.9
Fiscal Performance	59.59	5.24	58.91	43.64	75.996
Victims (index)	2.99	2.59	2.63	-0.15	12.78
Forced displacements†	1690.29	1384.22	1374.25	154.3	8390.2
Affected by landmines†	5.88	6.19	3.35	0.1	34
***Stable partially-forested municipalities* (681)**					
Population	26725.72	63342.86	11499.9	896.5	899489.4
Coca area	14.95	70.311	0	0	953.5
Forests commons	4020.38	37148.85	0	0	814620.1
Unsatisfied Basic Needs Index	40.17	18.07	38.08	5.36	100
Distance to markets	112.12	73.27	95.53	0	545.20
Land GINI	0.70	0.09	0.71	0.26	0.98
Fiscal Performance	60.08	5.94	59.25	39.91	83.35
Victims (index)	-0.23	0.68	-0.46	-0.55	7.06
Forced displacements†	214.68	443.17	60.35	0	7145.8
Affected by landmines†	0.32	0.90	0	0	15.1
***Stable non-forested municipalities* (261)**					
Population	31691.12	89361.59	13225.3	1162.5	1151094
Coca area	7.11	45.56	0	0	443.6

Forests commons	590.52	4606.98	0	0	54479.12
Unsatisfied Basic Needs Index	46.67	18.68	45.47	9.24	91.68
Distance to markets	106.57	75.82	82.042	0	308.75
Land GINI	0.68	0.09	0.68	0.38	0.91
Fiscal Performance	57.85	5.298	57.35	45.41	81.26
Victims (index)	-0.30	0.57	-0.49	-0.55	4.18
Forced displacements†	158.21	287.64	49.3	1.5	1818
Affected by landmines†	0.26	1.22	0	0	12.4

† Variable used to construct the Victims index